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INTEGRATED PERSONAL PROTECTIVE EQUIPMENT STANDARDS SUPPORT MODEL

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The National Institute of Standards and Technology's Office of Law Enforcement Standards (OLES) develops performance standards for equipment used by law enforcement personnel. The OLES and the U.S. Department of Homeland Security are developing a set of standards to protect first responders during incidents that may involve chemical, biological, radiological, or nuclear materials. The law enforcement community is interested in standards that are specific to their missions. A literature search was performed to identify the impacts of chemical protective suits, respirators, gloves, and boots on law enforcement tasks. A plan is described to develop a computer model using decision, sensitivity, and risk analyses to focus data collection and model development so that valuable information regarding performance of law enforcement tasks will be available to support the development of law enforcement-specific standards for personal protective equipment in a timely manner. The total cost of this 2-year project is estimated to be $500-600K.

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PREFACE

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INTEGRATED PERSONAL PROTECTIVE EQUIPMENT STANDARDS SUPPORT MODEL

1. INTRODUCTION

The National Institute of Standards and Technology's (NIST) Office of Law Enforcement Standards (OLES) develops performance standards for equipment used by law enforcement personnel. The performance standard development process begins when the law enforcement community identifies the need for a piece of equipment to perform at a certain level. The OLES determines how the equipment is used in the field and the conditions under which it is used. Research projects are initiated and the capabilities of commercial equipment are evaluated. The OLES then specifies the minimum performance criteria for the equipment and develops procedures to test the equipment. The minimum performance standard comprises the performance criteria and the test methods.

1.1 Need for Law Enforcement Standards

The OLES is also assisting the Department of Homeland Security (DHS) in developing a set of personal protective equipment (PPE) standards to protect first responders during incidents that may involve chemical, biological, radiological, or nuclear (CBRN) materials. In 2004, DHS adopted three National Institute for Occupational Safety and Health (NIOSH) respiratory equipment standards and five National Fire Protection Association (NFPA) protective suit, clothing, and respirator standards. The respiratory standards were for the air-purifying respirators (APR), self-contained breathing apparatus (SCBA) and air-purifying and self-contained escape respirators. The clothing standards were for protective ensembles for urban search and rescue operations, open circuit SCBA for fire and emergency services, vapor protective ensembles for hazardous materials emergencies, protective ensembles for chemical and biological terrorism incidents, and protective clothing for emergency medical operations (to protect against exposure to blood and body fluid-borne pathogens).

Law enforcement officers don't feel that these existing standards from NFPA and NIOSH fully apply to their missions. Participants in a user focus group indicated that a single PPE design would not work for the different missions for patrol, Special Weapons and Tactics, and Explosive Ordnance Disposal. Nolan also questioned the decision to adopt fire fighter PPE standards for law enforcement officers. He stated that even though officers are entering the same CBRN environment, their mission and tactics used to accomplish that mission are different. Nolan also discussed the concept of a *Crisis Phase* and *Consequence Phase* for a terrorist CBRN event. Law enforcement is mostly involved in the *Crisis Phase* – handling the immediate threat resulting from the release of the CBRN agent. Fire fighters will be primarily involved in the *Consequence Phase* after the immediate threat has been removed. Law enforcement officers will move at a fast pace and will take more risks. Their PPE must allow them to perform their jobs. Firefighters can move at a slower pace and can minimize risk exposure using PPE. Nolan further suggests that law enforcement must clearly define its mission at a CBRN event, identify the tasks that are required to achieve this mission, and then develop standards that allow them to perform these tasks while providing as much protection as possible.

One of the conclusions from sessions conducted by RAND Science and Technology Policy Institute and NIOSH on protecting emergency responders was that "protecting the health and safety of law enforcement responders may be the most challenging

personal protection task within the (emergency responder) community." One reason cited for this is the fact that patrol officers are often the first to arrive at a scene and therefore do not have all the information about hazards present at the scene. An example of this is when the police encounter a methamphetamine laboratory while responding to a domestic disturbance call. Police officers face several other obstacles. First, they are generally on patrol during calls unlike fire fighters who leave the station wearing their protective gear. Some police departments store protective gear in the trunk of a police vehicle, but it is not as handy in an emergency. Second, because they are on patrol between calls, police officers don't have the same amount of time for training that fire fighters do. Third, officers are concerned with appearance. If they show up wearing a helmet, it could show that they are anticipating violence. Fourth, police need to be able to run, operate their weapons, and participate in covert operations while wearing PPE. Finally, most PPE was not designed for law enforcement missions but rather has been adapted or adopted from other services such as the military or fire fighters. For these reasons, the law enforcement community is interested in standards that are specific to their missions.

1.2 Location of Operations

Law enforcement missions may occur in areas with varied levels of contamination. The U.S. Department of Transportation's Emergency Response Guide identifies three hazard zones for a CBRN event. The hot zone immediately surrounds the release site and extends far enough to protect personnel outside the zone from exposure. The cold zone is the area where command and support functions operate. The warm zone lies between these two areas and is where decontamination, control of access corridors, and hot zone support occur.

1.3 PPE Equipment

Officers responding to a CBRN event would need to wear chemical protective ensembles. These ensembles consist of respiratory protection, gloves, footwear, and suits.

1.3.1 Respiratory Protection

The types of respiratory protection that may be worn by officers responding to a CBRN event include APR, powered APR (PAPR), or a SCBA. The type of respirator worn will depend on the mission and the level of protection required.

The APR has a tight-fitting full facepiece with a filter canister attached to the side or front of the mask and may have either a single or dual lens system. While single lenses offer greater peripheral vision, they usually interfere with sighting a shoulder-fired weapon more than the 2-lens system. These respirators cannot be used in oxygen deficient atmospheres and are not recommended for use in the hot zone unless agent and air quality monitoring have indicated that they would be acceptable. The APR is used on the perimeter of the warm zone and in the decontamination area.

The PAPR is also a tight-fitting, full facepiece respirator but it has a belt- or backpack-mounted battery-powered blower that forces air through the filters and into the facepiece. The blower decreases the breathing resistance and permits larger filters to be used. The PAPR has several disadvantages. The blower adds weight, may interfere with movement, and creates noise that would impact the stealth ability of tactical officers in particular.

Additionally, the hose may be used to dislodge the respirator from the face or may become crimped. The cost of a PAPR is higher than that of an APR.

The SCBA has a facepiece with air supplied from a tank carried on the back or from an airline connected to a stationary source. It is required in areas where the agent hazard or concentration is unknown, or when the oxygen concentration is unknown or deficient. The SCBA air tank only supplies 30-45 min of air and adds weight while the airline may hinder movement or become crimped. Communication is generally worse with the SCBA than with the PAPR or APR. Finally, the cost is high and maintenance is more extensive.

1.3.2 Gloves

Latex gloves, used to protect against blood-borne pathogens, offer negligible protection against chemical warfare agents (CWAs). Chemical protective gloves may be made from several different materials. Butyl rubber gloves worn with cotton glove liners are often used to protect against CWAs. The gloves are available in different thicknesses. While protection will be greater with the thicker gloves, dexterity will decrease. It is important to balance the competing requirements of high protection and required dexterity.

1.3.3 Footwear

Protective footwear is worn to protect against exposure that would occur by walking through liquid CWA. Footwear consists of boots that are either worn directly on the foot or over shoes, or booties that are attached to the suit. Additional footwear must be worn over the suit booties to prevent them from tearing, although the outer footwear doesn't need to provide CWA protection.

1.3.4 Suits

Chemical protective suits may be made from permeable, semi-permeable, or impermeable materials and may be either a one-piece coverall or a two piece suit. Hoods attached to some suits should not replace the hood that comes with the respirator as the suit hood frequently leaves a gap at the neck that could allow agent penetration. A totally encapsulating suit provides a vapor-protective barrier and completely covers the wearer, including the respirator.

Permeable suits are lined or impregnated with charcoal. They should not be worn when there is a danger of getting wet as this decreases the protection level of the suit and may allow agent to be absorbed through the fabric. There is less heat build-up with these suits due to air transfer. They are durable and generally made from a dark material suitable for tactical operations, but are more expensive than impermeable suits.

Impermeable suits can be exposed to water and are less expensive than permeable ones. However, they have higher levels of heat buildup, tear more easily, and are noisy to operate in. They are often made from white or bright materials rendering them ineffective for stealth operations.

1.3.5 Other Equipment

The chemical protective equipment needs to be compatible with the other equipment that officers wear or carry in their normal duty routines. The items worn or carried will depend on the officer's mission. For example, for a patrol officer, these items include duty uniform, duty belt, pistol, body armor, handcuffs, baton, flashlight, and radio. A tactical officer will also wear a helmet and hearing protection and may carry a rifle or secondary weapon, flash bang grenades, ballistic shield, door ram, and breaching charges.

1.4 Protection Levels

The Occupational Safety and Health Administration specifies four levels of PPE based on the degree of protection provided. Level A equipment is selected to provide the highest level of skin, respiratory, and eye protection. Equipment for this level includes: pressure-demand, full-face SCBA, totally encapsulating chemical-protective suit, chemical-resistant outer and inner gloves, chemical resistant boots with steel toe and shank, and optionally, coveralls, long underwear, and hard hat. Level B is used when the highest level of respiratory protection is needed, but a lower level of skin protection is required. The required equipment is pressure-demand, full-face SCBA, hooded, chemical-resistant clothing, chemical-resistant outer and inner gloves, chemical-resistant boots with steel toe and shank, and optionally, face-shield, long underwear, chemical-resistant boot covers, and hard hat. Level C is specified when the threat is known and the criteria for using APR are met. This level requires the following: full-face or half-mask APR, hooded, chemical resistant clothing, chemical-resistant outer and inner gloves, chemical resistant boots with steel toe and shank, and optionally face-shield, escape mask, chemical resistant boot covers, and hard hat. Finally, Level D, a work uniform, provides minimal protection and is only used for nuisance contamination. Level D equipment includes coveralls and safety boots while the following equipment is optional: face-shield, escape mask, safety goggles, chemical resistant boot covers, and hard hat.

1.5 CBRN Exposure Situations

Officers may be exposed to chemical agents when responding to a known or suspected terrorist incident or may encounter a chemical agent when they first arrive on a scene when responding to another type of call. Law enforcement may also be exposed to chemical agents when they are securing the scene of a terrorist event and when they are establishing perimeters at the scene. Tactical officers may be exposed to chemical agents while apprehending a suspect at a terrorist event, taking down a subject who possesses a chemical agent, raiding a suspected chemical terrorist facility or laboratory, rescuing a hostage, or protecting dignitaries.

The chance of exposure will depend on the officer's mission. However, the mission of law enforcement officers responding to a CBRN event has not been well-defined. Several groups have developed or are in the process of developing characterizations of law enforcement missions for CBRN incidents. First, Arca and co-workers (1999) at the U.S. Army Soldier Biological Chemical Command (SBCCOM) evaluated chemical protective suits for law enforcement, and in doing so, specified tasks that would be required to be performed in PPE. A follow-on effort provided guidelines for PPE for law enforcement and established several mission profiles. Second, the Law Enforcement Advanced Protection (LEAP) program is in the process of developing mission profiles. Third, the Respiratory Protection Team members at the

Edgewood Chemical Biological Center (ECBC) developed a list of law enforcement-related tasks for a range of motion study they are conducting. Finally, the National Tactical Officers Association (NTOA) is currently developing a list of tasks officers would be expected to perform at a CBRN incident site.

1.5.1 SBCCOM Mission Profiles

The SBCCOM study identified the law enforcement CBRN missions as initial response, scene security, perimeter security, security of critical infrastructure, and operations in the warm zone. For the initial response, police officers must be able to recognize the symptoms of chemical agent exposure in potential victims. Additionally, dispatchers should be aware of multiple calls reporting symptoms that correspond to chemical agent exposure. Scene security will likely involve two or three levels of control and must consider the physical layout as well as contamination and cross-contamination. Perimeter security will include both outer and inner perimeters. The outer perimeter security will involve controlling pedestrian and vehicular access into and out of the incident location. The report recommended Level D PPE be worn by these officers, but that Level C equipment be kept nearby. The inner perimeter is the perimeter of the warm zone. The report recommended that Level C PPE be worn due to the danger of exposure from shifting winds, secondary releases, and cross-contamination from victims with agent on their clothing or belongings. Activities at this perimeter will include controlling crowds, ensuring entering personnel are wearing the appropriate PPE, and ensuring exiting personnel have been decontaminated. Critical infrastructure that needs to be secured includes hospitals and other medical facilities, buildings in other locations, and possibly, conferences, meetings, and exhibits.

Operations in the warm zone included searching for secondary devices, securing personal property, securing police equipment, arresting and detaining suspects, and investigating and processing the crime scene. It was recommended that recon in outdoor areas may use Level C, but in the hot zone, Level A must be worn. The belongings of citizens in the area need to be secured, including pictures or videos. Officers would need to secure and control ("bag and tag") clothing and belongings left by citizens for personal identification and as potential evidence. Police equipment, including badges, radios, uniforms, and fire arms, must be secured for officers who are decontaminated or for those who are casualties or fatalities. Suspects will need to be detained and arrested, although the report recommended waiting until the suspect had been decontaminated. The SBCCOM report stated that most of the crime scene processing will be done by the FBI as local officers will not need to perform rapid collection of evidence from the scene. Local HAZMAT teams with Level A suits will likely collect agent samples. Level A suits would be required for crime scene investigators. The report discussed whether patrol or tactical officers should perform these operations in the warm zone. It advocated using tactical officers because their equipment is better maintained, they are better trained for operating in PPE, they have more time for specialized training, and it is more cost effective to get them high quality PPE rather than try to outfit all patrol officers. The disadvantages of using tactical officers were that many of the operations are more consistent with patrol officer duties, using some tactical officers would break up the team, and using the tactical officers for these duties would reduce their ability to rapidly deploy to an area that required a tactical response. Departments would need to decide what worked best for them.

The study suggested specific missions and tasks for patrol officers and tactical officers. Patrol officers would be responsible for security of the external and inner perimeters and of the decontamination corridor. External perimeter security would involve traffic control and control of the major access ways. The security of the inner perimeter would require similar activities, but would be performed at the edge of the warm zone. Securing the decontamination

corridor would include crowd control and securing law enforcement sensitive equipment and personal property that require decontamination and/or may be evidence. They suggested that patrol officers would perform external perimeter security, inner perimeter security, and security of the decontamination corridor, while tactical officers would apprehend suspects, take down suspects who possess a chemical agent, raid a suspected chemical terrorist facility or laboratory, rescue hostages, and provide protection for dignitaries. Typical tasks patrol officers would perform included standing, walking slowly (2.5 km/hr), directing traffic, operating a radio, knocking on doors/performing evacuation procedures, running (5 km/hr), shouldering a firearm, sitting, and handcuffing suspects. Tactical officers would perform the following tasks to accomplish their missions: forced entry through doorway, building entry and reconnaissance, clear areas of a building, sight and discharge a weapon, take down a suspect, climb ladder or stairs to evaluate overhead conditions, moving along walls, rescuing hostages, and maneuvering through the building including crawling, climbing, and crouching. These missions and tasks are outlined in Table 1. The report recommended that any officer responding to a terrorist incident be provided at least a respirator and chemical protective gloves. Impermeable suits were recommended for patrol officers because the level of protection is on par with that of the respirator being worn and there is a possibility of water exposure in and around the decontamination corridor. It is also less costly when outfitting every patrol officer.

Table 1. Mission Profiles and Corresponding Tasks

Duty Assignment	Task
Patrol Officer	standing
	walking slowly (2.5 km/hr)
	directing traffic
	operating a radio
	knocking on doors/performing evacuation procedures
	running (5 km/hr)
	shouldering a firearm
	sitting
	handcuffing a suspect
Tactical Officer	forced entry through doorway
	building entry and reconnaissance
	clear areas of a building
	sight and discharge a weapon
	take down a suspect
	climb ladder or stairs to evaluate overhead conditions
	moving along walls
	rescuing hostages
	maneuvering through a building including crawling, climbing, and crouching

1.5.2 LEAP Program Mission Roles

The LEAP program identified five law enforcement mission roles: first responder/reporter, perimeter control, tactical operations, crime scene investigation, and personnel and equipment decontamination. Their First/Responder/Reporter is the first officer at the scene who recognizes the CBRN incident and implements the response communication

plans. The perimeter control officers secure the area, preserve the crime scene, control access to the three isolation zones, and provide security. Tactical operations in a CB environment would include alleviating threats, apprehending suspects, searches and seizures, evacuations, and rescues. Crime scene investigation officers would process the crime scene and conduct mortuary activities. Decontamination personnel would be responsible for clean-up and decontamination of victims, responders, and all contaminated equipment, although these tasks are usually carried out by fire service personnel. Tasks that the LEAP program identified for each mission role are shown in Table 2. Attendees at a working group meeting suggested the following tasks be added: communications (face to face), radio communications, rescue operations, CB perimeter characterization, and unassisted equipment donning. The LEAP program recommends that mission lengths for tactical operations be 6 hr or less while perimeter control and crime scene investigation be 12 hr or less.

Table 2. Tasks for Five-Mission Roles Identified by LEAP Program

Tasks	Mission Roles				
	First Responder	Perimeter Control	Tactical Operations	Criminal Investigation	HAZMAT
Weapons Proficiency	•	•	•		
Operate Equipment	•	•	•	•	•
Close Quarters Battle - tactical situation	•	•	•		
Ground Fighting - hand-to-hand	•	•	•		
Fire & Movement	•	•	•		
Engage Moving Targets	•	•	•		
Weapons Transition	•	•	•		
Night/Low Light Engagement	•	•	•		
Self-Defense	•	•	•		
Suspect/Victim Control	•	•	•		
Weapon Retention	•	•	•		
Traffic Direction/Crowd Control	•	•			
Evacuation	•	•	•		
Site Security	•	•	•	•	•
Assistance of Other Responders	•	•	•	•	•

Table 2. Tasks for Five-Mission Roles Identified by LEAP Program (continued)

Tasks	**Mission Roles**				
	First Responder	**Perimeter Control**	**Tactical Operations**	**Criminal Investigation**	**HAZMAT**
CBRNE Sampling, Monitoring		•		•	•
CBRNE Evidence Collection			•	•	•
Vehicle Operations	•	•	•	•	•
Decontamination (victims, public, LE personnel)					•
Decontamination (equipment, weapons, vehicle)					•

The LEAP group also identified physical activities that would be performed to accomplish the above tasks. They suggested activities and then also added responses from law enforcement personnel attending LEAP workshops, as shown in Table 3.

Table 3. Sub-Tasks Required to Complete LEAP-Identified Law Enforcement Activities

Physical Tasks Identified by LEAP	Physical Tasks Added by Attendees
Running	Pushing
Crawling	Pulling
Kneeling	Writing
Twisting	Talking, Responding
Jumping	Sitting
Climbing	Walking
Standing Extended Periods	Drinking/Re-hydrating
Lifting	Sighting a Weapon
Laying Prone	Facial Gesturing (for communicating)
Manual Dexterity	Using Keypad/Laptop
Hearing Acuity	
Visual Acuity	

The LEAP program working group also identified three possible operational scenarios, one for each of the mission roles. The perimeter control scenario will involve one person; the tactical scenario, four to eight personnel; and the crime investigation scenario, two personnel. The exact activities and measures of performance have not been set as of this time. The first responder/reporter role could occur in any of the three zones. Crime scene investigation and tactical operation would occur primarily in the hot and warm zones. Decon would occur in the warm zone. Perimeter control would operate in the cold and warm zones and also at the edge of the hot zone. A possible list of tasks and subtasks is provided in Table 4 below for each scenario. Possible performance measures include time and ability to complete each task.

Table 4. Operational Scenarios for Law Enforcement Mission Roles Specified by LEAP

Step	Perimeter Control Tasks	Tactical Operations Tasks	Crime Investigation Tasks
1	Don CB gear unassisted.	Don CB gear with assistance	Don CB gear with assistance.
2	Get in vehicle and drive farther away from incident scene.	Walk sideways along wall for 20 ft., stopping at closed door that opens in (away from approaching individuals). Climb 6 ft. wall, fence, or ladder.	Walk 25 ft. to crime scene stepping around "X" marks on floor placed 2 ft. apart and on different sides of a narrow pathway. Push/pull wheeled box of equipment around obstacles and through pathway.
3	From starting mark, run 50 ft. to area to be controlled.	Force open door with explosive breach and ram. Covert communication between officers.	Approach a table with a 2-in. square marked off at the far side of the table.
4	Secure caution tape around one item; roll out at least 10 ft. of tape, and secure other end.	Toss a "flash bang" grenade into doorway from position aside door.	Videotape crime scene. Place a measuring device next to evidence for relative size.
5	Run back 50 ft. to starting mark.	Enter doorway. Use shoulder weapon, switch to holstered weapon, re-holster and reload primary weapon.	Use proper handling techniques, wearing multiple layers of gloves, and removing properly to prevent cross-contamination.
6	Use radio to call command post. Write down instructions received via radio from command post.	Enter area beyond doorway.	Bend forward as needed to use fingerprint kit to powder, dust and tape the print, and then remove the tape and secure the print on the tape. Photograph fingerprint prior to placing in bag.
7	Retrieve notebook and pen. Draw rough sketch/map of scene.	Multiple room clearings	2-way radio communication to command: What is being picked up and how is it being labeled.
8	Walk back to caution tape, stepping over a guardrail on the way.	Go downstairs into dark/low light basement (possibly incorporate night vision devices)	Move 4 ft. to the side, and locate small item (e.g., pin from O'Conner test) on floor. One officer labels evidence bag and holds open. Second officer squats, picks up item with tweezers, and places item in bag. Secure paper bag. 2-way verbal communication between officers.

Table 4. Operational Scenarios for Law Enforcement Mission Roles Specified by LEAP (continued)

Step	Perimeter Control Tasks	Tactical Operations Tasks	Crime Investigation Tasks
9	Duck under tape, walk 20 ft. to 'victim'. Grab 'victim' under the arms and remove from cordoned-off area. Ensure 2-way verbal communication with victim is possible.	Have 2-way communication between team members, both verbal and radio.	Stand up, move 6 ft. further to same side. Squat down, retrieve digital camera and take photo of "object" on floor.
10	Once in safe area, render first aid to victim by wrapping upper arm with bandage.	Speak appropriate verbal commands to person lying on floor 10 ft. inside door, while keeping weapon trained on person. 2-way communication between officer and suspect.	Use atmospheric monitoring equipment to monitor and sample CB agents.
11	Stand up and repair any damage to caution tape caused from dragging dummy to safe area outside perimeter.	Approach person.	Stand, secure all items collected or used as necessary, move 6 ft. backwards, then turn around and walk back to starting point.
12	Walk back (50 ft.) to starting area.	Kneel next to person. Holster weapon. Use flex cuffs to restrain the person's arms behind his back.	Decon officers and equipment.
13	Take out flashlight, turn it on, and pan across area beyond caution tape. Stow flashlight.	Drag person out the door by grasping him under the arms.	Doff gear
14	Draw weapon from holster, hold upward with two hands for 10 s. Re-holster weapon securely.	Use "grab handle" on back of suit to drag a downed officer.	
15	Run approximately 10 ft. to other end of caution tape.	Decon officers and equipment.	
16	Re-draw weapon, aim, speak appropriate commands, and simulate firing 2 shots. Remove magazine from weapon, stow it, remove new magazine from belt and insert new magazine into weapon. Re-holster weapon.	Doff gear	
17	Decon officer and equipment.		
18	Doff gear		

1.5.3 ECBC Range of Motion and Aerosol Tests

The ECBC Respiratory Protection Team identified law enforcement specific tasks for their range of motion (ROM) and aerosol tests. For ROM, these tasks included: move head side to side; move head up and down; head lateral flexion; lift arms overhead; twist torso side to side; direct traffic; sit and stand; reach for the floor and ceiling; on hands and knees, turn head side to side; sight a rifle; sight a pistol; lunge; and, climb stairs. For the aerosol tests, these were normal breathing; move head side to side; move head up and down; recite the Rainbow Passage; lift arms overhead; twist torso side to side; sight a pistol; climb stairs; seated rest; direct traffic; sit and stand; reach for the floor and ceiling; on hands and knees, turn head side to

side; sight a rifle; lunge; and walk on a treadmill. Tasks were selected to represent LE tasks that would impact the integration of CB PPE equipment.

1.5.4 NTOA Survey

The end user survey being conducted by NTOA has not been completed. The law enforcement tasks proposed will be considered when the results of the survey become available.

1.5.5 Summary of Law Enforcement Mission Roles and Tasks

The SBCCOM, working in conjunction with law enforcement, identified a series of tasks likely to be performed by officers who would be wearing chemical protective gear. Tasks were identified for both patrol and tactical officers. They focused on specific movements that the officers would need to perform to successfully complete their missions. The tasks identified by the ECBC Respiratory Protection Team are similar in scope. They identify specific types of movements that officers would need to be able to perform, without specifying what the officer's mission was. The LEAP identified tasks are specified separately for each mission role, though many types of tasks overlap. The tasks identified by LEAP are likely too extensive to comprise a set of tasks for a standard. Furthermore, it is not necessary to test every scenario in which an officer would wear PPE. Rather, an approach similar to that used by SBCCOM and ECBC that would specify specific movements that officers need to perform (e.g., move head side to side) would be more suited to tasks for a standardized test.

2. LITERATURE SEARCH

The databases for the National Library of Medicine and the Defense Technical Information Center were searched to find information on the impact of PPE on task performance. Search terms included gloves, respirator, footwear, hood, boots, suits, chemical, resistant, protective, law enforcement, officers, police officer, protection, clothing, equipment, agility, dexterity, nuclear, biological, chemical (NBC), CBRN, marksmanship, firing accuracy, performance, biomechanics, personal protective equipment, individual protective equipment, human, model, and exercise. These terms were entered individually and in various combinations. An additional search was performed using the search engine "Google".

2.1 Physiological Impacts of Wearing PPE

Physiological and performance consequences occur when PPE is worn. Respiratory protective devices hinder vision, communications, respiration and personal support (wiping of nose, drinking). Problems occur due to sweat accumulation and heat build-up inside the mask, gloves, and suit. The added weight of the equipment increases the physiological work, hinders movement, and can cause sore muscles with extended wear. The influence of each of these factors depends in part on the work intensity and the type of task. Other important factors to consider are variability in response, anxiety, and hypoventilation.

These problems and others were expressed by attendees at a user workshop sponsored by Natick as part of LEAP development. Participants identified the following problems with PPE: range of motion, the amount of noise created by the suit, difficulty hearing, the suit fabric material was not breathable and was bulky, heat build up, the plate armor is not

compatible with SCBAs or CB suits, masks interfere with shoulder-fired weapons (cheek to stock welds), communications are hindered, and the head protection is heavy and bulky. Weapon issues mentioned were manual dexterity, holstering, reloading, aiming, and achieving consistent sight pictures.

2.1.1 Respiratory Protective Masks

Much research has been done on the impact of a respiratory protective mask on the wearer's physiology and performance. The physical characteristics of the respirator, such as inspiratory and expiratory resistance, dead volume, and mass, affect individual physiological response and impede performance. Additionally, communication, vision, and heat exchange with the environment are impacted. A person's anxiety level may also affect performance during respirator wear. However, even homogeneous subjects will have varied responses to wearing a respirator, and this variability must be considered.

2.1.1.1 Breathing Resistance

A person wearing an APR must overcome the resistance to breathing caused by the filter and the inspiratory and expiratory valves in the mask. Performance time decreases due to inhalation and exhalation resistances. Minute ventilation also decreases with increased resistance for low to high intensity work rates. Breathing at a lower minute volume than normal is termed hypoventilation. The hypoventilating person must extract more oxygen from each breath because the oxygen requirements of the body are unaffected by the decreased minute volume. An SCBA causes an increase in heart rate and oxygen consumption and a decrease in the maximal aerobic capacity. Oxygen consumption for moderate intensity exercise (60% of maximal aerobic capacity) was 13% higher when a filtering device was worn, 7% higher when an air-line breathing apparatus was used, and 20% higher when an SCBA was used.

2.1.1.2 Dead Volume

Dead volume, or dead space, is the amount of air present that does not take place in respiration. It is increased when an object, such as a snorkel, mask, or breathing tube, is placed over the mouth and/or nose. Carbon dioxide accumulates in the dead volume, causing it to act as a respiratory stimulant. Johnson, et al. found that for every 100 mL of added dead space, a 5.5% decrease in performance occurred for subjects exercising at 80-85% of maximum aerobic capacity.

2.1.1.3 Mass and Load Placement

The mass of any PPE or equipment that is worn or carried will increase the external work rate. Some metabolic load and work rate equations such as those developed by Pandolf et al. and Aoyagi et al. included total mass (body mass plus load mass) in the calculations. So, it is easy to account for the added weight of the respirator, clothing, PPE, or equipment. However, if the external work is specified and not calculated, the external work rate must be increased by the percentage increase in mass represented by the PPE and equipment. Thus, if the mask has a mass equal to 1.4% of the normal body mass of a man, the physical work rate for a person wearing that mask would be increased by 1.4% to account for the added mass of the mask. A recent study comparing a new rucksack design to the traditional SCBA showed that the distribution of the weight is important as well. Twelve firefighters performed simulated fire-fighting and rescue exercises wearing either the rucksack design or an SCBA with the same volume and similar weight. Performance times were faster and heart rates lower for

the rucksack-shaped SCBA compared to the traditional cylindrical SCBA. So, center of gravity and possibly moment of inertia may be important factors to consider.

2.1.1.4 Communications

Communication ability may be significantly degraded by respirators. Some CBRN respirators have a voice projection unit (VPU) to increase speech intelligibility. Two studies were conducted to quantify the effect of respirators on speech intelligibility between two subjects speaking across a room and on the telephone. The first study compared intelligibility of both sentences and single words across distances ranging from 0-12 m for subjects wearing APR. Single words were unintelligible at 9 m and greater. Sentence use resulted in performance ratings of 74% and 70% at 9 m and 12 m, respectively. So, at distances where single words are useless for communicating, sentences are intelligible a majority of the time. Furthermore, to achieve the same performance rating, the speaker and listener would need to be 10 m closer if single words were used instead of sentences.

The telephone study was intended to simulate radio communications. Different combinations of respirators, speech amplifiers, and hoods were used. Only monosyllabic words were used. While accuracy only suffered 10% on average, it took subjects 33-50% longer to identify the words depending on the equipment worn.

2.1.1.5 Vision

Vision during respirator wear can be impacted due to the decrease in visual field of view or to decreased visual acuity, which may occur due to fogging of the lenses. The influence of visual acuity on task performance depends on both the task and work intensity. During work at low rates, such as console monitoring or rifle firing, visual acuity is important. However, for console monitoring, a respirator is not likely to impact performance, but for activities that require peripheral vision, performance may be impacted if wearers cannot turn their heads to compensate. For activities at higher work rates, visual acuity becomes less important and thus has less of an impact on performance. There are high intensity activities that require good visual acuity, such as having to follow directional signs while running, but for the most part, moderate and heavy work rates depend less on visual acuity than do lower work rates.

Vision problems may cause additional problems with stability, orientation, and signal detection response time. Protective eyewear was found to have a negative impact on postural stability for twenty college students. The authors suggested that this would impact a sensory-challenging task such as climbing ladders or scaffolding. Paramedics performing resuscitation wearing an APR preferred a panoramic lens to a binocular lens for improved orientation. The tightness of the PPE on police officers' necks and peripheral vision problems during simulated tactical operations led to more hand and shoulder contact along the walls, which could cause increased exposure to liquid agent. Finally, visual signal detection response time was found to increase significantly for subjects wearing chemical protective clothing, with a hot environment (33 °C) exacerbating the performance decrement compared to the temperate (21 °C) or cool (13 °C) environments. This has implications for many law enforcement activities such as officers monitoring incident sites or tactical officers searching for suspects.

2.1.1.6 Thermal Environment

When a respirator is worn for an extended period of time, sweat accumulation inside the mask may become a problem. Johnson, et al. found that when subjects sat in a warm, humid environment (35 °C and 90% relative humidity) for 90 min, an average of 0.203 g sweat/min was generated from the face, head, and neck. The average facial skin temperature rose 2 °C during the test period even though subjects were acclimated to the heat.

Thermal sensation and respirator comfort have been shown to be related to face temperature for air-supplied respirators and APR. Nielsen, et al. reported that without a respirator, lip temperature was a linear function of ambient temperature ($r = 0.84$). When a respirator was worn, the lip temperature was independent of ambient temperature but was dependent on the temperature of the air supplied to the respirator. A decrease in the acceptability of the thermal conditions inside the respirator correlated to increasing respirator discomfort.

2.1.1.7 Anxiety

Psychological factors can play a large role in whether or not a person can tolerate respirator wear. To determine the amount of influence such factors have, Johnson et al. conducted an exercise study in which subjects took the Spielberger State-Trait Anxiety Inventory (STAI) to assess their anxiety level. Twenty subjects exercised at 80-85% of their age-predicted maximum heart rate until their volitional end-point. The performance times of subjects classified as non-anxious (STAI scores <34) were unrelated to the STAI score. However, a performance decrement occurred for anxious subjects. Someone with a STAI score of 40 would suffer a 25% performance decrement; while a highly anxious person (STAI score of 70) would have a 79% decrement and would therefore only achieve a 21% performance rating.

2.1.1.8 Performance of Other Tasks

The ability to accurately solve cognitive problems was not impacted by wearing a chemical protective mask and gloves, although the gloves decreased manual dexterity and subsequently increased performance time over the control condition. However, little decrement in performance was found for subjects wearing a respirator for 10 hr while performing exercises that rotated between light (cognitive), moderate, and heavy work periods.

2.1.1.9 Variability

There is often much variability in the responses of human subjects when performing various tasks. This occurs even if the subjects are very similar. Johnson et al. showed that 3 of the 12 subjects were not sensitive to inspiratory resistance and indeed showed little performance decrement. A study examining the effects of exhalation resistance found that 3 of 10 subjects could perform no treadmill work when the resistance was very high, but that the other 7 were able to perform for 2-10 min. Finally, the performance of subjects who scored an anxious rating on the Spielberger State-Trait Anxiety Test was dependent on the numerical score, while those classified as non-anxious had performances unrelated to their score.

2.1.2 Gloves

The selected glove must protect the officer, but must also allow the officer to perform duties that require manual dexterity, such as firing, reloading, and holstering a firearm. If thickness is decreased to improve dexterity, there is a greater likelihood that the gloves will rip. Dexterity problems with protective gloves have been well documented.

Dexterity tests performed while wearing butyl rubber gloves showed that glove thickness was directly related to task completion time. For one study using thicknesses of 0.18, 0.36, and 0.64 mm, there was a linear increase in task performance time relative to the thickness of the glove. Cognitive problems solved while wearing gloves took longer to complete due to the decreased manual dexterity. So, related activities may be impacted. However, chemical protective gloves did not impact the ability of personnel to operate a handheld video transmitter designed for surveying possible NBC-contaminated sites. And, pistol marksmanship scores for a weapons proficiency test for officers wearing chemical protective clothing (MCU2P respirator, 7-mil butyl rubber gloves, butyl rubber boots, standard Maryland State Police duty uniform and one of four impermeable suits) only differed by one or two points among the suit conditions and were reported to be essentially the same as those recorded during testing in the standard duty uniform. However, loading the magazine took longer in the PPE than in just the duty uniform. Dexterity has been shown to improve as subjects become more experienced with the gloves.

Glove damage would hinder protection. One study showed that damage occurrence (tears) was inversely related to thickness. Officers in the SBCCOM investigation had problems with the fingers of their 7-mil butyl rubber gloves ripping when they reloaded pistol magazines.

2.1.3 Footwear

Little information was available on the impact on performance when wearing chemical protective footwear. However, the static coefficient of friction (SCF) is an important parameter for assessing the soles of footwear. Hall evaluated the friction of several different sole materials on walkways made from stainless steel, aluminum, and new and worn non-skid coated steel. The surfaces were dry, wet, or contaminated with oil. The tested footwear included the Navy safety foot with nitrile rubber sole, a Vibram nitrile commercial sole, the Army prototype nitrile/neoprene multipurpose overboot (MULO) and vinyl overshoe, and three-butyl chemical protective footwear covers. The standard and MULO nitrile soles performed best overall. The author stated that the high SCF across surface conditions combined with the chemical resistance of the nitriles made them good materials for chemical agent protective footwear. No minimum or recommended SCF was provided.

2.1.4 Suits and Ensembles

Chemical protective suits and ensembles create a barrier to prevent agents from reaching the skin of the wearer. However, these suits impact task performance and mobility and interfere with the body's ability to exchange heat with the environment.

2.1.4.1 Task Performance

Several studies investigated the ability of medical personnel to perform procedures such as intubation, antidote administration, and trauma and life-saving tasks such as CPR while wearing various levels of PPE. While these activities would not be performed by law enforcement officers, the tasks in these studies do involve dexterity and vision and would involve movements similar to those used for tasks such as collecting evidence or rendering first aid.

Coates et al. found that doctors and nurses could successfully perform life-saving tasks while wearing chemical protective suits with a respirator, although one of the ten participants was unable to intubate in ,<30 s. However, Garner et al. found that medical procedures took significantly longer in Level-A PPE compared to Levels C and D. The performance times were not statistically different between Levels B and C. Arad et al. found that the time to perform medical trauma tasks increased by approximately 30% during 8 hr of wearing chemical protective suits. The authors noted that prior training and experience in performing medical tasks in PPE were important factors in successfully completing trauma tasks. So, the level of protection and the length of wear may increase the time to complete the tasks, but these effects may be mitigated with training.

White and Hodous investigated the impacts of protective clothing and respirators on tolerance times of subjects performing light (30% of maximum work capacity) or moderate (60%) exercise. Four conditions were used: light work clothing, light work clothing with SCBA, firefighter turnout gear with SCBA, and chemical protective suit with SCBA. Mean tolerance times at the low work rate were 167, 130, 26, and 73 min for the four conditions. At the moderate intensity, mean times were 91, 23, 4, and 13 min, respectively. Wearing the SCBA significantly decreased the tolerance time even when subjects were wearing lightweight work clothes. The performance rating is 44% for the fourth clothing condition for low intensity work and 14% for the moderate intensity work. Thus, the PPE imposes a severe performance limitation on the wearer, even at low exercise intensities. Wearers cannot work as long or as hard as they could without PPE.

2.1.4.2 Mobility

Huck found that the design of protective clothing and equipment impacted mobility as measured by a flexometer. Adams and Keyserling investigated the impact of size and fabric weight on mobility using a goniometer. Garment size significantly impacted ROM for all measured movements except for shoulder extension and trunk lateral flexion. Undersized garments caused the largest decrements in ROM. Fabric weight impacted shoulder extension and elbow, hip, knee, and shoulder horizontal flexion. While no measurements of range of motion were made, officers performing tactical exercises including marksmanship trials did note a decrease in mobility while wearing an MCU2P respirator, 7-mil butyl rubber gloves, butyl rubber boots, standard Maryland State Police duty uniform and one of four impermeable suits compared to the standard duty uniform.

2.1.4.3 Thermal Effects and Heat Strain

When exercise occurs in or below the thermal comfort zone, the core temperature is independent of the environmental temperature; it depends only on the metabolic level of the exercise. Exercise above the thermal comfort zone depends on environment and clothing conditions. The ability of the person to exchange heat with the environment depends

on air temperature, radiant temperature, vapor pressure, air speed, and the insulation and vapor transfer values of the clothing. Additionally, the air movement created by self-fanning (air movement generated by moving body parts) must be considered. Tolerance times in hot environments have been shown to be impacted by hydration level, fitness, and gender, but not by short-term heat acclimation.

Cheung and McLellan investigated the impact of hydration levels on heat tolerance for subjects performing light and heavy exercise in the heat while wearing NBC protective clothing. Tolerance times were significantly impacted even by minor levels of hypohydration for both exercise intensities. A follow-on study by the same authors assessed the impacts of heat acclimation and aerobic fitness in addition to hydration levels. Tolerance times were not affected by short-term (two week) heat acclimation, but the highly fit individuals were able to work significantly longer than the moderately fit subjects.

McLellan found that tolerance times were significantly longer for males than females for intermittent exercise performed in a 40 °C environment while wearing NBC protective clothing. The core body temperature rose significantly faster for the female subjects. The rate of heat storage was similar but the rate of heat storage per body mass was significantly lower for females. However, when subjects were matched for body fat, tolerance times and heat storage were not significantly different. The authors concluded that females are at a significant disadvantage when wearing PPE in the heat and that this can be attributed to the generally higher percentage body fat of females and the lower specific heat of adipose tissue compared to non-adipose tissue. So, gender is an important factor to consider.

Heat strain was investigated for six males performing 20 min of moderate exercise in three environmental conditions (21.5 °C, 28 °C, and 31.5 °C with sunshine) while wearing the fully encapsulating Coast Guard Chemical Response Suit and SCBA. The mean heart rate rose 40 bpm for the hottest temperature compared to the control condition while skin temperature was 4 °C higher. Core temperature did not increase significantly. The heart rate at 5 min after the end of exercise was significantly higher for the warmer environmental conditions. The authors concluded that impermeable chemical protective clothing causes an increase in heat strain as ambient temperature increases.

2.1.4.4 Task Performance in the Heat

Tikuisis et al. found that neither cold nor heat thermal strain degraded marksmanship for subjects firing a rifle at moving or pop-up targets. Core body temperatures were between 36.4 °C and 37.9 °C. The authors performed a follow-on study in which body temperatures were increased to 39 °C over the course of 4 hr through a combination of exercise and passive heating. Again, there was no degradation in marksmanship due to heat strain and whether subjects were hydrated or dehydrated.

However, cognitive performance in the heat (33 °C) declined after 4-5 hr for subjects wearing chemical protective clothing. Percent error was 17-23% higher after 7 hr of PPE wear in the heat than for control conditions for investigator-paced tasks. For a self-paced task on map plotting, productivity decreased 40% after 6 hr in the heat during PPE wear compared to the control conditions. The accuracy of the map plotting was not significantly impacted. So, accuracy was maintained on the self-paced task by increasing performance time. When performance time was maintained on tasks by the investigators, accuracy declined.

2.1.5 Summary of Physiological Impacts of PPE

When PPE is required for performing even low intensity exercise tasks, shorter work periods and longer, more frequent rest periods are required. Several studies showed that there was a trade-off between performance time and accuracy for tasks such as communications, visual signal detection, and manual dexterity tasks. However, training may mitigate some of the performance decrements. Tolerance times in hot environments may be impacted by hydration level, fitness, or gender, but not by short-term heat acclimation. Hot environments degrade visual signal detection response time and cognitive performance. The variability in response to respirator wear across the population underscores the necessity of using large sample sizes in conducting studies and in calibrating and validating models. Thus, the trade-off between performance time and accuracy, the hydration level, fitness, experience, and gender of the person wearing the PPE, the intensity level of the activity, the thermal environment, and the physical characteristics of the PPE (glove thickness, breathing resistance) are all important considerations for standards development.

2.2 Existing Models

Many models have been developed that predict the performance impact of various PPE components on performance. However, no single existing model includes a comprehensive analysis of the impact of changes in PPE design parameters on the physiological load or performance. Even so, these models provide valuable information that would be beneficial to consider for a comprehensive model.

2.2.1 Respirator Encumbrance Model

The Respirator Encumbrance Model (REM) predicted the performance of respirator wearers based on physical and material mask design parameters and specific military tasks. Twenty human performance capabilities were specified during the development of REM, while 51 mask design parameters were identified that were thought to impact these capabilities. The capabilities and design parameters are listed in Tables 5 and 6. The REM contains a list of over 1000 military tasks and their related subtasks. For example, for the pistol maintenance task, the subtasks would be clearing the pistol, disassembling the pistol, cleaning the pistol, assembling the pistol, and performing a function check.

Table 5. REM Human Performance Capabilities

Human Performance Capability	Description/Definition
Auditory mental processing	The amount of auditory processing that a situation entails ranging from registering to interpreting a particular sound
Balance	Postural stability required
Binauralism	Does/does not require two ears
Biomechanics/Head & neck movement	Movement that is required of the head and neck
Cognitive mental processing	The amount of cognitive processing that a situation entails ranging from simple association to calculation and conversion
Comfort	The relationship between sources of psychological distress and mask components
Dead space	Volume of inspired air that is re-inhaled from the preceding exhalation
Depth perception/Visual binocularism	Vision in both eyes is required to form a single, fused, stereoscopic image
Fatigue-endurance	Time to run 2 m
Field of view sight	Field of view when using a rifle sight or similar sighting device
Expiratory resistance	Resistance to expired airflow imposed by the respirator and its expiratory valves/components
Visual and peripheral field of view	Visual field of view
Hearing threshold-high frequency	Minimum decibel level required to detect high frequency sounds (> 1 kHz) some distance away
Hearing threshold-low frequency	Minimum decibel level required to detect low frequency sounds (≤ 1 kHz) some distance away
Inspiratory resistance	External resistance to inspired airflow imposed by the respirator and its filter element(s)
Psychomotor mental processing	The amount of psychomotor processing that a situation entails ranging from speech generation to serial manipulation
Speech intelligibility	Level of communication required by the intelligibility scale
Thermal burden	Physiological impact of relationship between mask materials and environmental factors
Static visual acuity	Clarity of vision required to see stationary objects of different sizes at different distances
Visual mental processing	The amount of visual processing that a situation entails ranging from detection to monitoring of an object

When the REM is started, the user inputs information on the mask and the task to be performed. The user either selects an existing mask design or inputs new mask design parameters for communications, vision, protection, and respiration. The task or set of tasks (called a "mission" within the model) is selected. The *Task Requirements*, or expected human performance under normal conditions (without a respirator) are then specified for each subtask. For instance, the capability scores for the subtask clearing the pistol were: visual acuity = 3; visual field of view = 2; visual binocularism = 1; cognitive mental processing = 3.7; visual mental processing = 4; psychomotor mental processing = 5.8; head/neck movement = 1; with the remaining capabilities = 0. The higher the value, the more important the capability is to that subtask. The impact of mask design on capabilities is determined next using algorithms developed for the REM. The capabilities during mask wear are then compared to capability

requirements for tasks and subtasks to determine the performance degradation in the form of a performance rating (masked performance/unmasked performance).

Table 6. REM Mask Design Parameters

Parameters		
Lens shape	Field of view	Lens area
Lens location	Lens orientation	Lens curvature
Lens width	Communication area	Voicemitter shape
Communication	Communication location	Communication orientation
Voicemitter material	Filter area	Filter thickness
Filter shape	Filter location	Filter pressure drop
Filter orientation	Inlet valve area	Inlet valve shape
Inlet valve location	Inlet valve pressure drop	Inlet valve orientation
Outlet valve area	Outlet valve shape	Outlet valve location
Outlet valve pressure drop	Outlet valve orientation	Nosecup area
Nosecup shape	Nosecup location	Nosecup orientation
Nosecup area	Nosecup shape	Nosecup location
Nosecup orientation	Dead space volume	Facepiece material
Mask suspension	Canister weight	Profile (canister)
Drink tube shape	Drink tube flow rate	Drink tube area
Drink tube location	Drink tube orientation	Drink tube length
Drink tube diameter	Hood thickness	Hood material

While the model produced reasonable results, there were shortcomings. The model did not include any pure physiological calculations and model results were never validated with human subject trials. When the REM was created, sufficient data were available to develop performance algorithms for comfort, dead space, fatigue-endurance, expiratory and inspiratory resistance, high frequency hearing threshold, visual and peripheral field of view, and speech intelligibility. Only five of these capabilities had sufficient data to relate performance to mask design parameters. Recently, Caretti and co-workers undertook an effort to re-examine the REM algorithms based on newly available data. Based on that review, they developed new algorithms for inhalation and exhalation resistance, thermal and mechanical comfort, vision, and communications. They noted that much of the required psychophysiological data needed to relate performance and respirator design components do not exist. Finally, the REM did not consider the impact on performance of PPE other than respirators.

2.2.2 Johnson, Coyne, and Chiou Models of Physiological Impact of Respirators

Johnson developed an outline of a mathematical model of the metabolic, cardiovascular, and respiratory effects of wearing a respiratory protective mask. Metabolic load, or physiological work, in the model was based on skeletal muscle work, basal metabolic processes, respiratory and cardiac requirements, isometric muscular work required for posture maintenance, and the effects of food ingestion. Both transient and steady-state responses were included. The first step of the model was determining the energy costs of muscular work and support functions such as basal metabolic rate, food thermogenesis, and posture support. These energy costs were then converted into oxygen requirements. The respiratory ventilation and amount of carbon dioxide production were determined from the oxygen requirements. The metabolic requirements of respiration and anaerobic respiration were then determined. Respiratory flow rates, respiration rates, waveshapes, and respiratory mechanics were obtained

next. Finally, model parameters were checked against known psychological and physiological limits. The model was conceptual and never implemented on a computer.

Coyne developed a model to predict the effects of a respiratory protective mask during constant rate exercise that was based on the concepts and structure presented by Johnson's model. The model was implemented using equations obtained from the literature, variable definitions, and small, related research studies. The model input parameters included an individual's age, fitness level, and maximal aerobic capacity, respirator characteristics (breathing resistance, dead volume, and mass), and the external work rate. Empirical equations were developed that related oxygen consumption to physiological work rate, anaerobic threshold, minute ventilation and tidal volume to oxygen consumption, and exhalation time to respiratory period. Respirator resistance and dead volume effects were quantified. Model outputs included predictions of minute ventilation, tidal volume, respiratory work, oxygen consumption, and a very rough estimate of performance time.

Results showed that the structure of the model was valid and that the model made rational predictions of the average effects of respirator wear on pulmonary system parameters during constant-rate physical activity. However, the model was unable to predict performance of individual subjects due to the large variability in human performance. This initial modeling effort laid the groundwork for the future development of a model to predict the metabolic impact of respiratory protective masks on workers performing various occupational tasks.

Chiou modified the Coyne model to include transient values of the respiratory parameters and a performance time based on work rate. The Kamon equation was used to predict performance time based on oxygen consumption and maximal aerobic capacity. Transient equations were added to the model for oxygen consumption, minute ventilation, and tidal volume. Transient oxygen consumption was predicted using a three-phase exponential equation. Minute ventilation and tidal volume were calculated as functions of oxygen consumption based on equations developed for Johnson's model.

Results showed that performance times predicted by the model for both respirator wearers and unencumbered subjects were not significantly different from measured times. Chiou graphed the predicted and actual data and reported that the revised model made predictions of transient oxygen consumption, minute ventilation and tidal volume following the trends in the experimental data. However, a statistical analysis of the predictive capabilities of the model was not performed.

2.2.3 Improved Performance Research Integration Tool

The Improved Performance Research Integration Tool (IMPRINT) is used to assess warfighter-system interaction. The model includes environmental stressors and nine Military Occupational Specialties (MOS). Each job or mission is broken down into a sequential list of tasks. The operator, performing the task, and the time to complete the task are specified. The operator must be specified because IMPRINT is used to model crews of workers performing tasks. The task network model uses stochastic modeling to provide a distribution of times, rather than a set, deterministic, performance time to incorporate the variability in human performance. Once the task network is entered into the software, the system operator's performance of the mission is simulated.

The user may also include the operator's mental workload using either a simple or advance workload analysis. The simple analysis uses the visual, auditory, cognitive and psychomotor (VACP) model. The designer estimates the mental workload values for each task, considering the mental resources the operator requires to perform each task. The designer selects the visual, auditory, cognitive, and psychomotor resources, or combinations thereof, that will be required to perform the task. The user then enters numerical values for each resource using a scale of 0-7. The assigned value depends on the behavior expected for the task. The Visual Workload Scale is shown in Table 7. The workload rating for each resource across concurrent tasks is summed. It is possible for the workload to exceed seven because the operator could perform two tasks at once. The software output includes graphs and tables of the workloads over time for each operator in the crew. This software can show where peak workloads occur, allowing the system designer to either automate tasks or decrease the resources required. Similarly, the results may show that one operator has a much heavier workload than another operator. The system could be modified to reassign some of the tasks to the second operator. While the VACP software is useful for early system designs, the operator's performance is not impacted by workload. The advanced workload option must be used to link workload to performance.

Table 7. Visual Workload Scale

Scale Value	Visual Scale Descriptor
0.0	No visual acuity
1.0	Visually register or detect (detect occurrence of image)
3.7	Visually discriminate (detect visual differences)
4.0	Visually inspect or check (discrete inspection or static condition)
5.0	Visually locate or align (selective orientation)
5.4	Visually track or follow (maintain orientation)
5.9	Visually read (symbol)
7.0	Visually scan, search, or monitor (continuous or serial inspection, multiple conditions)

Performance may decrease if the mental workload is too high or too low and at certain levels, there may be an increase in mental workload without any change in performance if the operator is able to compensate for the increased workload). The advanced workload analysis also requires the designer to specify the mission, the tasks the operator(s) will be performing, the task sequences, and which operator is performing which tasks. However, a workload model based on MRT is used to calculate workload. The model considers the resources being used, the equipment interfaces, and mental resources used. The advanced workload includes the four resources of VACP as well as speech and any user-defined resources, e.g., tactile. System designers use the seven-point scales to estimate required resources. The advanced workload analysis employs MRT to not just add the resource demands, but also imposes penalties when two tasks require the same resources at the same time or when the use of different resources causes interference. The designer must specify the amount of interference using a scale from 0 (no conflict) to 1 (total conflict). Workload is calculated for each operator prior to the task, at the start of the task, and at task completion. Outputs include a mission summary, critical path report, workload graphs, and reports on operator activity, overload, and conflicts. Periods of peak workload can be evaluated and the tasks modified, automated, or reassigned to another operator.

This model as it exists now would not support standards development as it uses mental workload rather than physiological workload to predict performance. However, the

model concept could be used to develop a physiologically-based model of teamwork that could prove useful for predicting performance for tactical teams.

2.2.4 Metabolic Work Rate

The metabolic work rate is an indication of the intensity of the task being performed. The total metabolic rate may be determined from various empirical equations or from tables of values.

2.2.4.1 Givoni and Goldman Model

Givoni and Goldman developed an empirical model for predicting the metabolic energy cost of level and grade walking on any terrain, with and without loads, at walking speeds of 0.7-2.5 m/s and running speeds from 2.22-4.72 m/s. The weight of clothing and equipment was included in the model. Corrections were made for load placement as metabolic load is affected by where the load is carried. Model results showed a correlation of 0.95 between predicted and measured values. The models were developed only for young, healthy, physically fit males.

2.2.4.2 Pandolf Model

Pandolf et al. continued the work of Givoni and Goldman by adjusting the equation to make predictions for subjects who were standing or walking very slowly (<0.7 m/s). The authors validated the equation with two studies and good agreement was found between the empirical model and the experimental results.

2.2.4.3 Limitations of Givoni and Goldman, and Pandolf Models

While both the Givoni and Goldman, and Pandolf, et al. models provided accurate results, both models have limitations. First, the equations were developed and validated using only male subjects. Second, neither model can be used for activities other than walking or running.

2.2.4.4 Other Methods

Tables may also be used to predict the metabolic work rate or a range of work rates for a specific task. Johnson provided a list of several tasks soldiers must perform and the corresponding work rates. Many of these tasks would be similar or identical to those performed by law enforcement officers. Examples include rifle firing, driving, walking, and running. No information was found on the metabolic cost of activities performed by police officers. Limited studies on metabolic work rates of military activities are available.

2.2.5 Heat Strain Models

There are many different heat strain models that have been developed. This is a well-defined area of performance modeling, although improvements are still possible and necessary.

The military has been instrumental in developing heat strain models to assess the impact of PPE on core body temperature during activity. Natick Labs and the

U.S. Army Institute of Environmental Medicine (USARIEM) have been at the forefront of model development.

Givoni and Goldman developed a set of empirical equations to predict core body temperature based on clothing, ambient temperature and humidity, and metabolic work load. Their equations produced relatively good results for healthy young males. However, hydration, gender, fitness, and solar heat load were not considered until subsequent work by Pandolf and co-workers.

USARIEM developed models that predict heat strain under varying conditions. Their models include enhancements of the Givoni and Goldman equations. Inputs include environmental parameters, work intensity, type of clothing, and acclimatization status. Outputs include body temperature, heart rate, sweating rate, tolerance or performance time, and others such as optimal work/rest cycles and hydration needs. These models provide realistic core temperature responses but require modifications to improve accuracy, particularly for low intensity exercise and tolerance times. The models continue to undergo improvement. Prediction accuracy has increased for heart rate and core body temperature by including an adjustment for the variation in individual initial core temperature and a correction for the metabolic rate for downhill activities. The model still under-predicts core temperature and heart rate during low intensity activities such as marksmanship training.

2.2.6 Other Models

McLellan et al. investigated the impact of PPE on work tolerance time in the heat for eight males exercising at light or heavy exercise intensity. Tolerance time was the time to reach core body temperature of 39.3 °C, 5 hr, 95% of maximum heart rate, or onset of dizziness or nausea. The authors found that there was a decreasing hyperbolic relationship between tolerance time and metabolic rate when PPE was worn.

Heat load can be reduced by increasing air permeability through the chemical protective suit. However, increased air permeability will decrease protection by increasing air velocity through the suit material. A theoretical model was developed to predict the total vapor breakthrough concentration through NBC-protective material based on parameters such as air velocity and challenge concentration. This model may be used to balance the competing demands of decreasing heat load and increasing protection levels.

2.2.7 Summary of Models

While no single existing model would support PPE standards development, they do offer useful information and ideas regarding approach and techniques. The method employed in the REM model could provide a useful framework for a comprehensive performance model while the approach to team tasks in IMPRINT could prove useful for modeling the response of tactical response teams. As heat strain and thermal environment have been shown to impact performance of people wearing PPE, the USARIEM and other heat stress models would be important to incorporate in the proposed modeling effort.

2.3 Summary of Literature Review

The law enforcement community is interested in PPE standards that have been developed specifically for their missions. A complete performance model would optimally support development of the desired standard. Such a model would allow the user to change important equipment design parameters such as glove thickness, helmet center of gravity, or respirator inhalation resistance and know the impact on the ability of a hypothetical person to complete a task and the time it would take to do so. This model would include respiratory, thermal, cardiovascular, metabolic, psychological, and cognitive effects. While much data have been collected in each of these areas, there are still many questions to be answered. Tying all of the information together will not be a simplistic process. The variability of human responses to homogeneous situations has proven to be a major challenge in predicting human performance. Such an all inclusive model would have benefits far beyond providing a basis for standards development. However, the standards development process, while time consuming, is not expected to take more than 3-5 years. Developing such an inclusive model would either take an extremely large sum of money or a very long time to complete. There are insufficient data and predictive equations available at this time to develop such a model. Human performance studies would be required to generate data from which equations could be developed. Therefore, such a performance model is not practical for supporting standards development in the relatively short time frame available. However, sensitivity analysis and risk analysis may be employed to focus the design effort on the PPE parameters that would most impact performance. These analyses would be used to direct development of a model to support standards development as well as any human performance studies required to obtain supporting data. While the resulting model would not be all inclusive, it would provide useful information for law enforcement PPE standards development.

3. DEVELOPMENT OF A STANDARDS SUPPORT MODEL

Development of a law enforcement PPE standards support model could be accomplished during a series of 10 tasks over the course of 2 years. This time frame would allow sufficient model development time while also ensuring that the resulting data were available during the standards development process. The first task would be to specify the law enforcement missions and the tasks and sub-tasks that are required to accomplish those missions. For the second task, protection data would be identified and if sufficient protection data were available for tasks, this information would be included in the model. The third task would identify or develop mathematical relationships that relate equipment and personnel characteristics to performance. A sensitivity analysis would be run to identify the parameters with the most impact on performance. A risk analysis would be performed to balance the cost of the data collection against the impact of the parameter on performance. Additional data collections would focus on the parameters with the most impact as identified through the sensitivity and risk analyses. Mathematical relationships would be updated based on the newly collected data. A software program that integrates the equations would be developed during the eighth task. During the ninth task, the model would be validated and modified as needed. The tenth and final task would focus on creating an executable software program with the required documentation.

3.1 List of Tasks

Task 1: Specify Law Enforcement Missions and Characterize Equipment
Task 2: Identify Relevant Protection Data
Task 3: Identify or Develop Mathematical Relationships
Task 4: Perform Decision and Sensitivity Analysis
Task 5: Perform Risk Analysis
Task 6: Collect Additional Data
Task 7: Update Mathematical Relationships/Equations
Task 8: Integrate Equations and Write Software Program
Task 9: Validate and Modify Model
Task 10: Produce Software Product and Provide Documentation

3.1.1 Task 1: Specify Law Enforcement Missions and Characterize Equipment

This task would identify law enforcement missions and the tasks and subtasks required to complete those missions. Physiological, environmental, and equipment-related factors that impact task performance would be identified. Finally, physical characteristics of fielded PPE would be identified. These characteristics would include parameters such as glove thickness, respirator resistance, and suit thermal conductance.

There are several efforts underway that are investigating law enforcement missions and the impact of PPE on task performance, range of motion, center of gravity, and moment of inertia. These results could be leveraged to develop accurate mission profiles, tasks, and sub-tasks that may be performed in a CBRN environment.

3.1.1.1 LEAP Programs

The LEAP group continues to meet with law enforcement personnel through user workshops to hone its characterizations of law enforcement missions. The latest rendering would be considered in developing missions for the model.

The LEAP research group also plans to conduct an ergonomics evaluation of COTS CBRN PPE. The group proposes to test subjects wearing only their duty uniform and then their duty uniform with each of three different CB suits (air permeable, selectively permeable, and impermeable) and the appropriate respiratory protection, gloves, and overboots. Subjects will participate in laboratory and field testing. Lab testing will consist of: donning/doffing ease and time; gross dexterity; fine dexterity; and gross body mobility, i.e., range of motion. The field testing will involve subjects completing three different missions (perimeter control, tactical operations, and crime scene investigation).

3.1.1.2 NTOA Survey

The NTOA will be conducting an "end user survey on law enforcement tasks that may have to be performed in a CBRN environment" (Nolan, 2007). Results of this survey could be meshed with the LEAP results.

3.1.1.3 ECBC Research Projects

The ECBC is currently conducting several research projects that would provide information useful for specifying law enforcement tasks and subtasks. These projects include: system level protection of integrated PPE, head-borne mass properties studies, and revisions of a human performance parameters database and algorithms. The information gleaned from these studies could be leveraged to support the model.

Head-borne PPE may impact an officer's ability to perform a mission because the PPE may affect movement and position of the head, neck, and upper torso. The ECBC is investigating the ROM of subjects performing law enforcement-type activities while wearing typical law enforcement PPE including suits, body armor, helmets, and respirators. The ECBC is also performing aerosol and vapor testing of the individuals wearing the PPE and performing the law enforcement tasks to determine the impact of PPE physical characteristics on protection factor levels.

The mass properties of the respirators, protective hoods, communications devices, and helmets that law enforcement officers may be required to wear when responding to a CBRN event may be a factor that impacts performance. Additionally, the CBRN filters are larger and heavier than non-CBRN filters. The ECBC is collaborating with the U.S. Air Force to investigate the impact of head-borne PPE on neck fatigue and comfort with the goal of correlating these results with unmanned test parameters such as center of gravity and moment of inertia. Current PPE standards do not set limits for head-borne mass properties.

The ECBC Respiratory Protection Team is updating the REM database and algorithms to support development of the next generation military respirator. Tasks and algorithms that apply to law enforcement activities and missions would be considered for inclusion in the model.

3.1.2 Task 2: Identify Relevant Protection Data

While much protection data have been collected, not all of it would be relevant to task performance. This is an area that may benefit from more extensive research. Raw data would be obtained from previous research studies. Additional data would be obtained from the authors of open literature publications and from theses and dissertations. These data would be included in the later risk analysis task so that the user may see how changes in the PPE characteristics impact the trade-offs between performance and protection.

3.1.3 Task 3: Identify or Develop Mathematical Relationships

This task would focus on collecting existing equations as well as developing new model segments for instances where they do not exist or are inappropriate for the current effort. Statistical modeling software could be used to develop the models. Data obtained from the literature would be used to develop and validate the model segments.

3.1.4 Task 4: Perform Decision and Sensitivity Analysis

This task would involve performing decision and sensitivity analyses to identify critical design paths and the variables that most influence the model outcome. Decision analysis is a systematic way of describing problems while taking uncertainty into account. In the

current research, the goal of the model would be to maximize performance while also maximizing protection. Decision analysis could be used to identify the critical decision path as well as a risk profile for all possible solutions. In addition to these quantitative results, decision analysis also provides insight into trade-off and conflicts of interest.

Sensitivity analysis involves varying the input parameters and assessing the impact on the model outcome. Variables with little impact may be replaced by their average values. Software would be used to try a range of values for each variable and provide the outcome for each value and combination of values. The results would identify which input variables affect the outcome the most. This information would be used along with the results of the subsequent risk analysis to guide further data collection.

3.1.5 Task 5: Perform Risk Analysis

While decision analysis provides results for typical or average values of input parameters, risk analysis assesses the chance of any result occurring. Risk analysis software may be used to perform a Monte-Carlo simulation to analyze every possible outcome and assess the risks of each. Probability distributions could be provided for each variable. Each distribution could be determined by fitting distributions to data obtained from prior research studies. Minimum and maximum values could be specified for each input parameter. The results from the risk analysis would provide insight into the trade-off between time, cost, and the impact of the collected data on the performance model.

3.1.6 Task 6: Collect Additional Data

During this task, human subject testing would be conducted based on the results of the sensitivity and risk analyses. The research studies would be conducted in conjunction with an area college or university. Male and female subjects whose ages are representative of law enforcement members will be recruited. A human subject protocol would be submitted to the review boards of both the selected academic institution and ECBC.

3.1.7 Task 7: Update Mathematical Relationships/Equations

This task would formulate new equations for the model based on data collected in Task 6. The new equations could be developed using statistical modeling software.

3.1.8 Task 8: Integrate Equations and Write Program

The focus of this task would be to integrate the updated equations from Task 7 with the prior equations identified during Task 3. The results of the sensitivity and risk analyses would also be used to refine the model. The resulting model would then be implemented in a computer program. A user interface would be developed that allows the user to enter subject information, physical characteristics of PPE and other equipment, and environmental conditions. The format for the output data would be established. At the conclusion of this task, a functioning model would be produced that predicts the metabolic impact of IPE wear on a soldier.

3.1.9 Task 9: Validate and Modify Model

For this task, model predictions would be compared to experimental data using statistical analyses. Both qualitative and quantitative analyses would be performed. Qualitative analysis includes graphing results and ensuring that the model predictions follow the general trends in the experimental data. Quantitative evaluation generally involves goodness-of-fit tests to determine how closely the model output agrees with experimental data. Based on these results, the integrated model segments may need to be modified. A validated model would exist at the conclusion of this task.

3.1.10 Task 10: Produce Software Product and Provide Documentation

Once the model is making accurate predictions, a deployable software product would be developed. This product would include an executable version of the model software that would run on any PC running Windows 2000/NT/XP. A user manual describing installation and operation procedures, including example program runs, would be developed. The executable software program and related documentation would be presented at the conclusion of this task.

3.2 Summary of Model Development

This work plan to develop a standards support model recommends using decision, sensitivity, and risk analyses to focus data collection and model development so that valuable information regarding performance of law enforcement tasks would be available to support the development of law enforcement-specific standards for personal protective equipment in a timely manner. A rough estimate of the cost of this two-year effort would range from $500-600K. Table 8 shows a timeline for completion of each task.

4. CONCLUSIONS

The law enforcement community is interested in PPE standards that are specific to tasks that they perform. It is first necessary to define law enforcement missions and the tasks and sub-tasks associated with those missions. While the LEAP program has drafted some mission profiles, the large number of tasks in those profiles is not realistic to include in a PPE standard. The tasks need to be down-selected to represent types of motions that officers will perform without requiring that each instance of that motion be included.

The research presented in the literature review shows that PPE impairs task performance even for low intensity tasks. There is often a trade-off between performance time and accuracy, though adequate training may mitigate some of the performance decrements. While much research has been performed, there are still data that are needed to develop a model to support standards development.

By using decision, sensitivity, and risk analyses, the number and cost, of research studies may be reduced. These analyses will allow this research to focus on those model input parameters that most impact task performance. Subject selection for the research studies is critical for getting realistic results. Due to the impact of training on performance, the subjects must be trained not only on the specific activity being performed, but also on the

equipment being worn, carried, or used. Subjects must be representative of active law enforcement officers with respect to age, gender, and physical fitness.

While a full performance model would ideally support development of a law enforcement-specific standard for PPE, the development time and cost required for such a model are not compatible with the standards development time frame. Therefore, a standards support model is recommended that employs various analyses to focus the research effort and data collection. It is anticipated that this support model could be developed in 2 years for an estimated cost of $500-600K. This model would provide valuable information on performance of tasks to support development of PPE standards for law enforcement officers.

Table 8. Timeline of 2-Year Project Indicating Month Tasks Will Be Performed

	Year 1												Year 2											
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Task 1: Specify Missions																								
Task 2: ID Protection Data																								
Task 3: Develop Equations																								
Task 4: Decision Analysis																								
Task 5: Risk Analysis																								
Task 6: Collect Data																								
Task 7: Update Equations																								
Task 8: Write Software																								
Task 9: Validate Model																								
Task 10: Finalize Product																								

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